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Doctoral Dissertation
Doctoral Program in Electrical Electronic and Communication Engineering
(38th cycle)

High-Fidelity Simulation Models for Advanced Control Design of Electrical Drives

By

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Abstract

The development of modern electrical drives relies on accurate modeling, simulation in dedicated environments, control design and experimental testing. Laboratory testing, however, is time-consuming, energy-intensive, and costly, so high-fidelity models are essential to validate motor control algorithms over a wide range of operating conditions before hardware implementation. This dissertation focuses on motor models for permanent-magnet and reluctance synchronous machines, addressing three main aspects: (i) the development of accurate models, (ii) the definition of experimental characterization procedures to calibrate such models and (iii) building on such models, the design of advanced control strategies for different operating conditions in industrial and e-mobility applications.

Regarding (i), a collaboration with Plexim GmbH, has led to the implementation of circuital models of the two main types. These models account for spatial harmonics, magnetic saturation, and iron and permanent-magnet losses through flux maps, and have been validated against both Finite-Element-Analysis (FEA) and experimental measurements. They are being integrated into the PLECS simulation environment and into the open-source SyR-e platform, including the case of multi-three-phase machines.

Regarding (ii), the accuracy of the proposed models is strongly dependent on underlying flux maps, which represent the intrinsic electromagnetic behavior of the machine. Although such maps can be obtained through FEA, experimental identification is preferred, to capture real-world phenomena that may be disregarded by the FEA. For the first time this work establishes an experimental methodology for the computation of the flux maps with spatial harmonics, referred to as $dq\theta$ flux maps. These maps include the oscillations in the flux linkages, thus the back-EMF, and torque ripple. Starting from the $dq\theta$ flux maps, innovative circuital models have been developed for integration in a circuit-based simulation framework.

Regarding (iii), the developed circuital models are employed for the design, testing and evaluation of control strategies for different emerging applications. In collaboration with Mitsubishi Electric Research Center Europe, two main control solutions have been implemented for synchronous reluctance motors in variable speed drives. The first one solves the real-time tracking of the Maximum-Torque-Per-Ampere (MTPA) operating condition without using Look-Up-Tables (LUTs). The second one is the sensorless control strategy for motor drive fed by slim-DC link, virtually with no DC link capacitance. Both control strategies are currently patent pending. In addition, the proposed modeling methodology used to investigate and validate the following problems: (i) torque ripple compensation in Direct-Torque-Control, (ii) sensorless control with High-Frequency injection, referred as High-frequency Active-Flux (HFAF), and (iii) Active-Short-Circuit (ASC) operation of traction motors.